IAUS 330

Gaia Mapping a Billion Stars

Gerry Gilmore

Thank you
to

Alejandra & SOC

Patrick & LOC

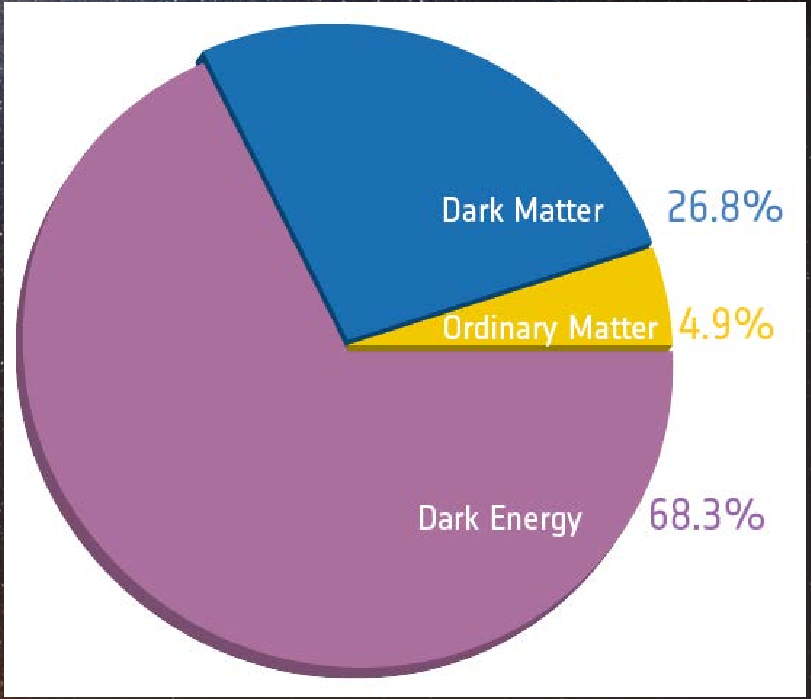
for a superb meeting

The organisation has been
excellent

The number of participants illustrates the
awareness and importance
of Gaia science

The origins of Gaia
Science case proposed vs today

FIG. 1. William Herschel's cross-section of the Milky Way.



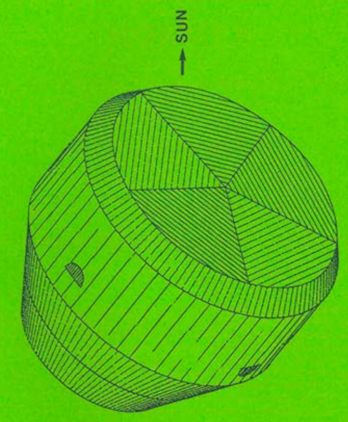
GAIA within Horizon 2000+

- Proposal for a super-Hipparcos (Roemer) submitted by E. Høg et al. in response to M3 invitation (1993); highly rated by AWG
- Interferometry had been foreseen as part of the ESA long-term plan ('green dream')
- Detailed proposal for an astrometric interferometer, GAIA, submitted in response to call for ideas for Horizon 2000+ (Lindegren et al., September 1994)
- Original target: 50 million objects at 10 microarcsec to 15 mag
- Accuracy/completeness/magnitude using small interferometer +CCDs
- Rated very highly by ESA-appointed Survey Committee: recommended as a cornerstone if 10 microarcsec could be demonstrated
- Cambridge Workshop in 1995 (ESA SP-379):
  - baseline interferometer design
  - direct fringe detection + dispersed fringes desirable
  - detailed elements of scientific case
- Funding for industrial study approved (Oct 1996) for studies commencing in 1997
- Parallel study of Infrared Space Interferometer (Darwin)
- Cornerstone 5 open (after XMM, FIRST); launch 2009, depending on science funding
- Hipparcos Symposium (Venice, May 1997): DIVA, SIM, LIGHT, ...

2

Perryman (ESA PS) summary at November 1997 Leiden meeting

Rotating Optical Observatory for Extreme Measuring Efficiency and Rigour



ROEMER

Proposal for the Third Medium Size ESA Mission (M3)

A mission dedicated to very accurate astrometric and photometric measurement of 10^8 stars

U. Bastian, G. Gilmore, J.L. Halbwachs, E. Høg, J. Knude, J. Kovalevsky, A. Labeyrie, F. van Leeuwen, L. Lindegren, J.W. Pel, H. Schrijver, R. Stabell and P. Thejll

Edited by L. Lindegren

Lund 1993

Response to Call for Mission Concepts for Horizon 2000 Follow Up
Proposal for an astrometric interferometer as an ESA Cornerstone Mission

GAIA

Global Astrometric Interferometer for Astrophysics

L. Lindegren, M.A.C. Perryman, U. Bastian, J.C. Dainty, E. Høg, F. van Leeuwen, J. Kovalevsky, A. Labeyrie, F. Mignard, J.E. Noordam, R.S. Le Poole, P. Thejll and F. Vakili

Summary

We propose that a small interferometer of the Fizeau type (baseline ~ 3 m), dedicated to global astrometry, should be studied as a possible concept for an ESA Cornerstone Mission. Positions, absolute parallaxes and annual proper motions could be determined with accuracies on the 20 microarcsec level. The observing programme could consist of all objects to a limiting magnitude around V = 15–16, or some 50 million stars, extragalactic and solar-system objects.

NOTE ON ROEMER PROJECT

by J. KOVALEVSKY

Is it necessary to have a large input catalogue ?

In Hipparcos and Tycho, the input catalogue plays a double role : to serve as the basic data for primary attitude determination and to limit the part of the sky in which useful data is to be obtained. The second role in the Hipparcos main mission desappears in Roemer since there is no image dissector. In the case of Tycho, the serendipity mode limits the use of TIC to a computing time saving device. All Tycho could have been treated in the serendipity mode. So, it is quite natural to ask oneself the question whether, for Roemer project, one needs an input catalogue for anything else but the determination of the attitude, and for this objective, Hipparcos output catalogue with possibly some adjunctions from Tycho or meridian catalogues would be quite sufficient.

The availability of CCD's is indeed a very fundamental technical advancement which permits the major breakthrough promised by this mission. But it is not the only one. One should also take into account the fact that on-board storage and computing possibilities have been increased by several orders of magnitude since 1980.

There are two ways of making profit of this fact.

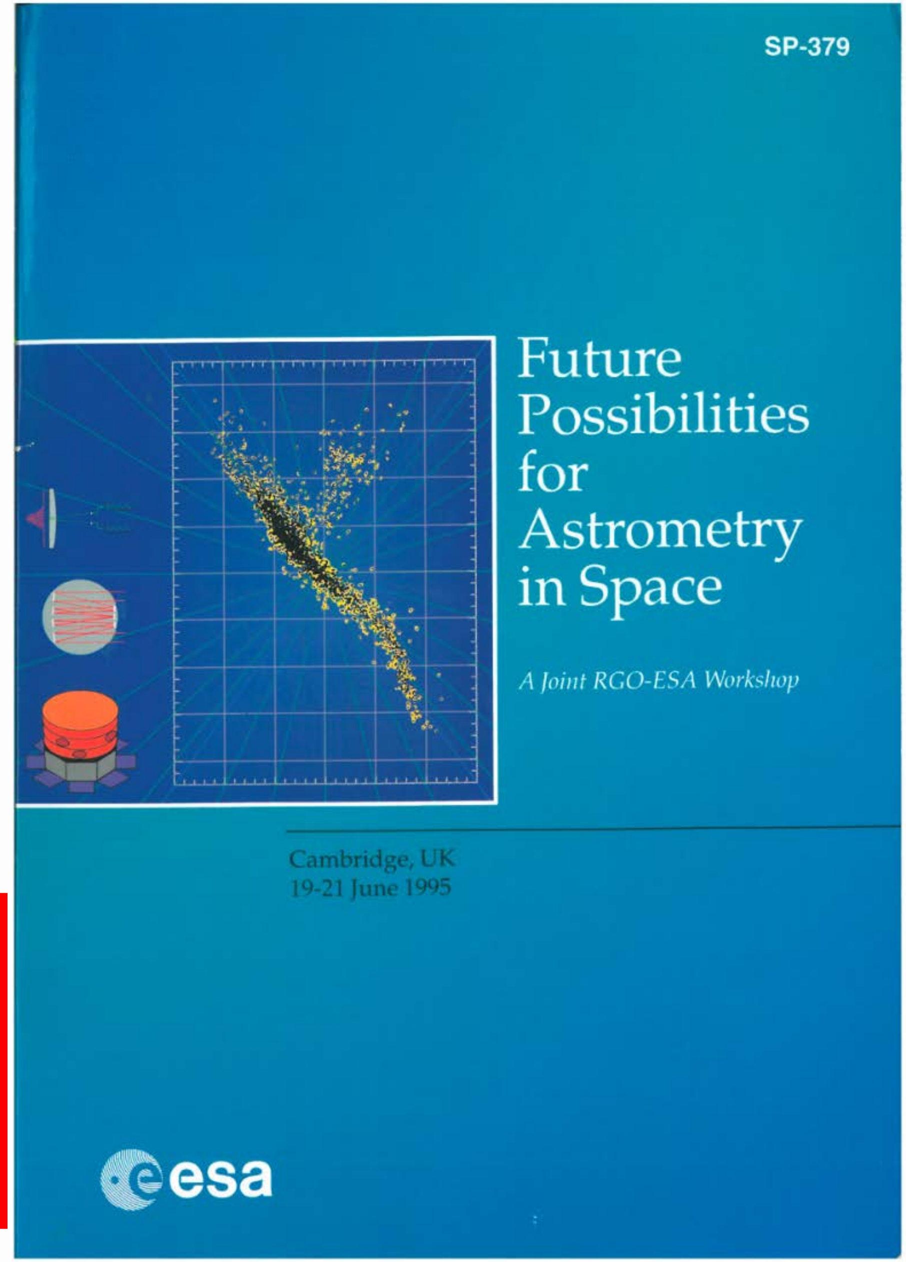
1. To recognize on-board all interesting objects and send to the ground those pixels that surround these objects.

2. In addition, to analyse the shape of the image and to compute on-board the few parameters that characterize the image, including the intensity, the position of the photocentre, second order moments and duplicity recognition.

Let us discuss this for one of the CCD's. All the 13 chips could be treated simultaneously in exactly the same manner with a small parallel computer (for instance 16 major processing units, 3 of which could be kept in case of damage on others).

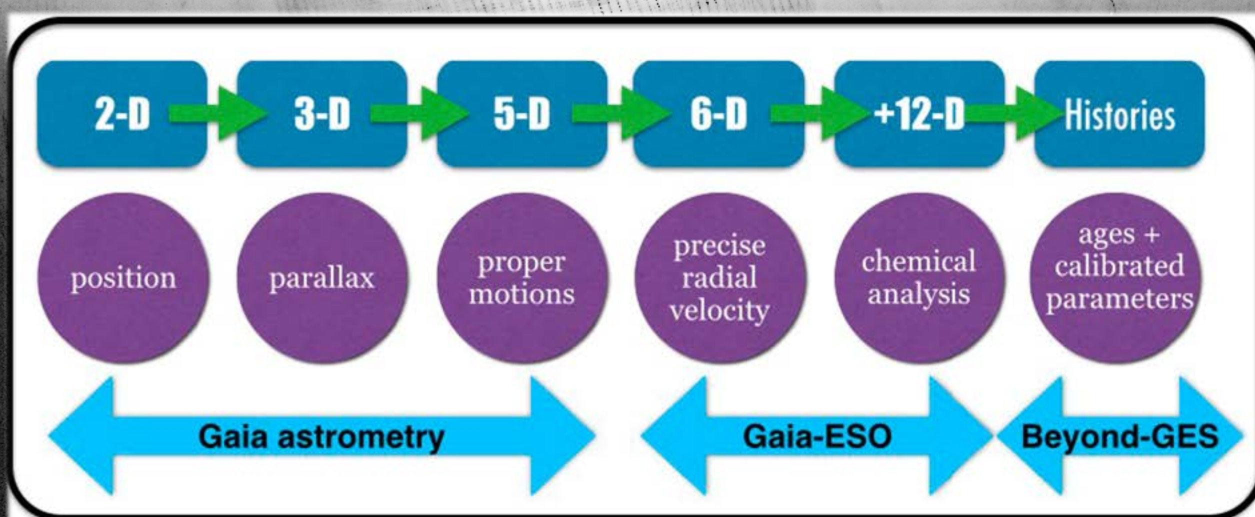
In compensation, the gain is enormous in comparison with the preparation of a 10^8 star input catalogue on the ground (significantly larger than the Guide Star Catalog, and therefore requesting a new world-wide program) and, in addition, it provides a very important plus by transforming the mission into a survey mission.

Grasse, May 5, 1993



Type of Data		Model Function		Physics
Kinematics	⟺	Dynamics	⇒	
radial velocities proper motions		phase space distribution function spatial distributions		gravitational potential dissipational history
Chemical Abundances	⟺	Chemical Evolution	⇒	
line strengths, photometry		star formation history ISM history		stellar initial mass function gas flows, dissipation, SFR
Luminosity Profiles	⟺	Galactic Structure	⇒	
colour–magnitude data surface brightness		spatial distribution function luminosity functions		stellar IMF, binarity, dissipation, SFR, ...

Proceedings of a joint RGO-ESA Workshop on Future Possibilities for Astrometry in Space, *Cambridge, UK, 19-21 June 1995*
(ESA SP-379, September 1995)



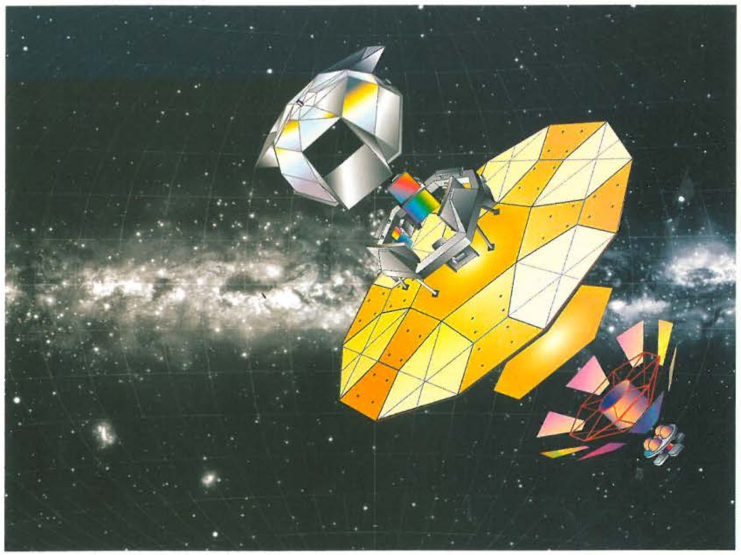
esa

ESA-SCI(2000)4
July 2000

Gaia “Red Book”

GAIA

Composition, Formation and Evolution of the Galaxy



Concept and Technology Study Report

European Space Agency
Agence spatiale européenne

GAIA Science Advisory Group (SAG)

- Funding for industrial study (600 kAU) assigned in early 1997
- SAG established under authority of D/Sci (R. Bonnet) in early 1997
- Four meetings: March, May, July, September 1997 (+4–5 November)
- Members:
  - G. Gilmore, Cambridge
  - E. Høg, Copenhagen
  - M.G. Lattanzi, Torino
  - L. Lindegren, Lund
  - F. Mignard, Grasse
  - S. Röser, Heidelberg
  - P.T. de Zeeuw, Leiden
- Study scientist: M. Perryman (SA); Study manager: O. Pace (Future Projects); F. Favata (SA); S. Volonté (D/Sci office, Paris)

&A 369, 339–363 (2001)
OI: 10.1051/0004-6361:20010085
) ESO 2001

Astronomy & Astrophysics

GAIA: Composition, formation and evolution of the Galaxy

M. A. C. Perryman[1], K. S. de Boer[2], G. Gilmore[3], E. Høg[4], M. G. Lattanzi[5], L. Lindegren[6], X. Luri[7], F. Mignard[8], O. Pace[9], and P. T. de Zeeuw[10]

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4 Copenhagen University Observatory, Juliane Maries Vej 30, 2100 OE Copenhagen, Denmark
5 Osservatorio Astronomico di Torino, Strada Osservatorio 20, 10025 Pino Torinese (TO), Italy
6 Lund Observatory, Box 43, 22100 Lund, Sweden
7 Universitat de Barcelona, Departament d'Astronomia i Meteorologia, Avda Diagonal 647, 08028 Barcelona, Spain
8 Observatoire de la Côte d'Azur, CERGA, Avenue Copernic, 06130 Grasse, France
9 Future Projects Division of ESA, ESTEC, Postbus 299, 2200 AG Noordwijk, The Netherlands
10 Sterrewacht, Jan Hendrik Oort Building, Postbus 9513, 2300 RA Leiden, The Netherlands

Received 1 November 2000 / Accepted 5 January 2001

Abstract. The GAIA astrometric mission has recently been approved as one of the next two “cornerstones” of ESA's science programme, with a launch date target of not later than mid-2012. GAIA will provide positional and radial velocity measurements with the accuracies needed to produce a stereoscopic and kinematic census of about one billion stars throughout our Galaxy (and into the Local Group), amounting to about 1 percent of the Galactic stellar population. GAIA's main scientific goal is to clarify the origin and history of our Galaxy, from a quantitative census of the stellar populations. It will advance questions such as when the stars in our Galaxy formed, when and how it was assembled, and its distribution of dark matter. The survey aims for completeness to $V = 20$ mag, with accuracies of about 10 μas at 15 mag. Combined with astrophysical information for each star, provided by on-board multi-colour photometry and (limited) spectroscopy, these data will have the precision necessary to quantify the early formation, and subsequent dynamical, chemical and star formation evolution of our Galaxy. Additional products include detection and orbital classification of tens of thousands of extra-Solar planetary systems, and a comprehensive survey of some 10^5-10^6 minor bodies in our Solar System, through galaxies in the nearby Universe, to some 500 000 distant quasars. It will provide a number of stringent new tests of general relativity and cosmology. The complete satellite system was evaluated as part of a detailed technology study, including a detailed payload design, corresponding accuracy assesments, and results from a prototype data reduction development.

GAIA

Composition, Formation and Evolution of our Galaxy

Cornerstone Presentations, Paris, 13 September 2000

Scientific Case:	P. T. de Zeeuw
Payload, Accuracy and Data Analysis:	L. Lindegren
Spacecraft and Mission Implementation:	O. Pace
Why, How and When:	G. Gilmore

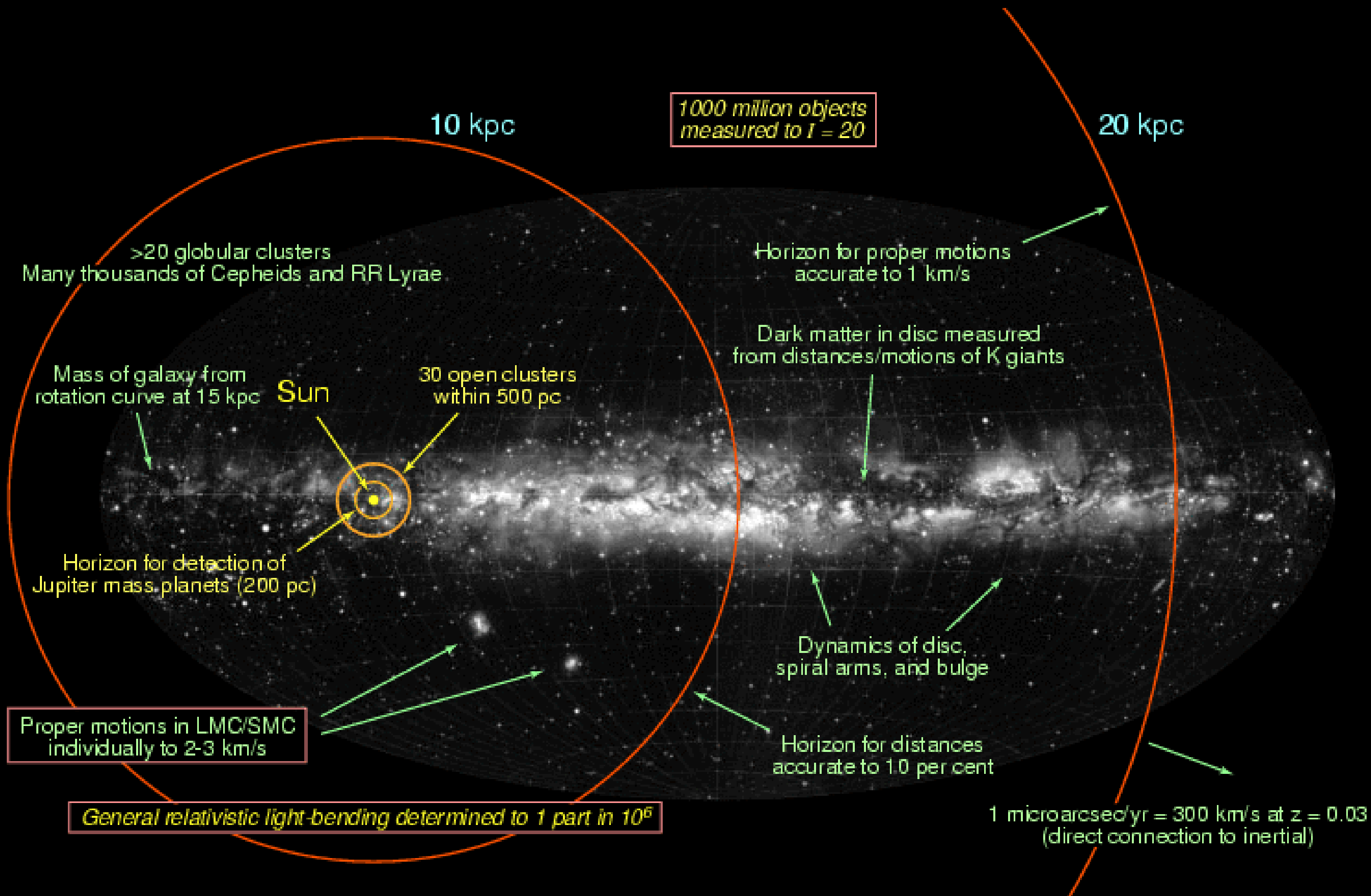
...on behalf of the GAIA Science Advisory Group, GAIA working groups, ESA Future Projects & Astrophysics Division, and industrial teams

Approved, Optimisation and budget saving continued

1.2 The GAIA Mission Development Background

In the framework of the "GAIA Concept and Technology Study", performed for ESA in 1998 by MMS-T, today Astrium SAS (F), a system design and development approach for GAIA was defined. Following the approval by the AC in their December 2001 meeting, the direct negotiation contract GAIA System Level Technical Reassessment Study was awarded to the company ASTRIUM SAS (F), with the main purpose to re-assess the GAIA technical baseline at a cost affordable to the present Science level of resources. The new GAIA feasible baseline found viable by ESA, has been presented for approval in the context of the rearranged Science Programme at the SPC on 22-23 May 2002 and approved for launch not later than 2012. However, the D/SCI management has decided to continue, for the time being, the GAIA technology developments in order to make possible a launch in mid-2010, as funds become available either through delay on other programmes or by increase in the Science budget.

GAIA Accuracies and our Galaxy



10 μas = 10% distances at 10 kpc

10 μas/yr = 1 km/sec at 20 kpc

GAIA: Key Science Objectives

- Structure and kinematics of our Galaxy:
  - shape and rotation of bulge, disk and halo
  - internal motions of star forming regions, clusters, etc
  - nature of spiral arms and the stellar warp
  - space motions of all Galactic satellite systems
- Stellar populations:
  - physical characteristics of all Galactic components
  - initial mass function, binaries, chemical evolution
  - star formation histories
- Tests of galaxy formation:
  - dynamical determination of dark matter distribution
  - reconstruction of merger and accretion history

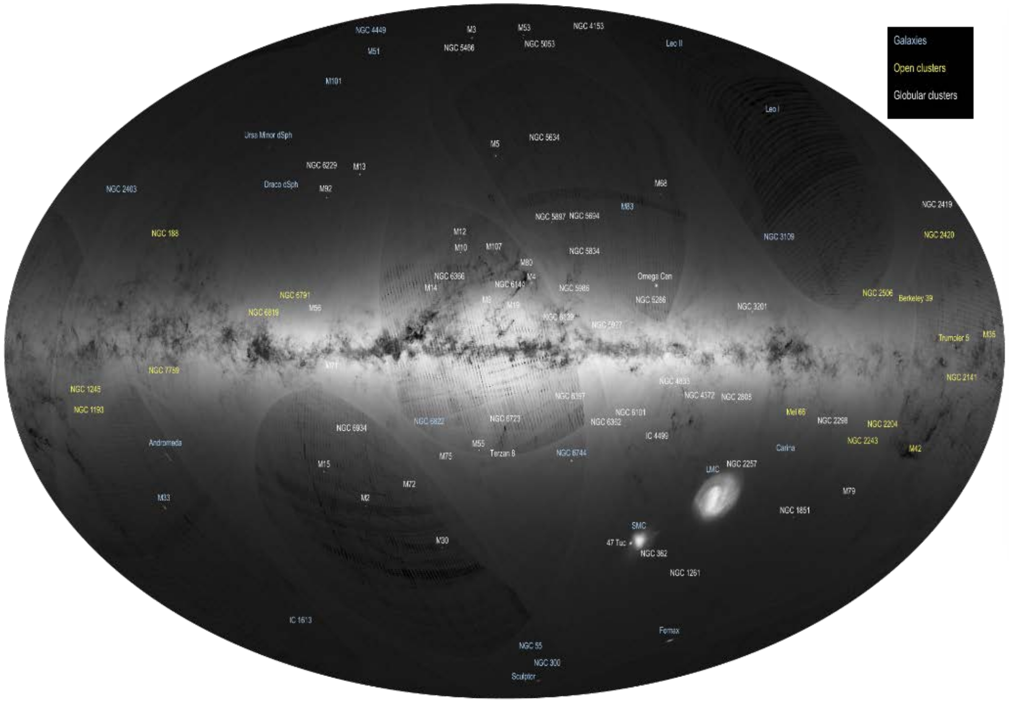
$\Rightarrow$ Origin, Formation and Evolution of the Galaxy

Stellar Astrophysics

- Comprehensive luminosity calibration, for example:
  - distances to 1% for 18 million stars to 2.5 kpc
  - distances to 10% for 150 million stars to 25 kpc
  - rare stellar types and rapid evolutionary phases in large numbers
  - parallax calibration of all distance indicators
    e.g. Cepheids and RR Lyrae to LMC/SMC

- Physical properties, for example:
  - clean Hertzsprung-Russell sequences throughout the Galaxy
  - solar neighbourhood mass function and luminosity function
    e.g. white dwarfs (~200,000) and brown dwarfs (~50,000)
  - initial mass and luminosity functions in star forming regions
  - luminosity function for pre main-sequence stars
  - detection and dating of the oldest (disk and halo) white dwarfs

Gaia’s first all-sky-map



Testing stellar evolution

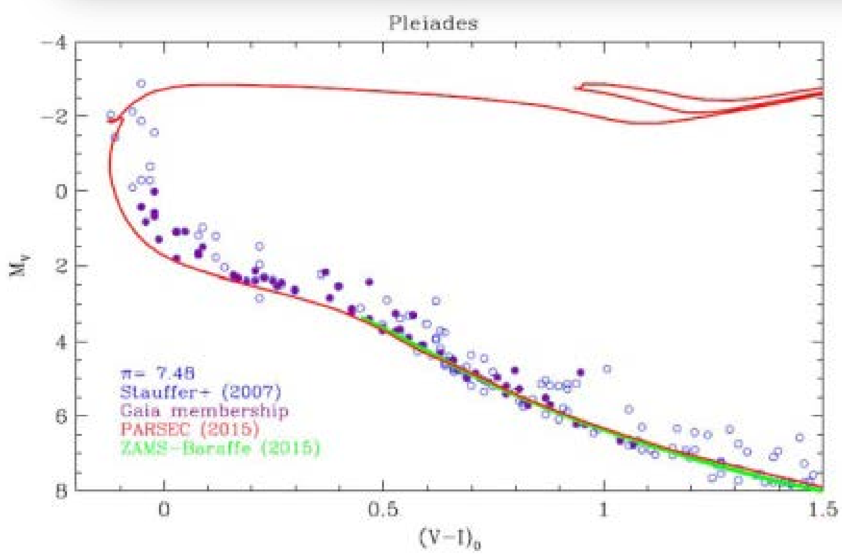


Fig. 25. M_V, $(B-V)_0$ HR diagram of the Pleiades, with several sets of commonly used isochrones (top). Bottom panel is the analogous in the M_V, $(V-I)_0$. We assume an age of 130 Myr, solar metallicity, A_V=0.1

Combine distance and apparent brightness to determine intrinsic properties of the stars in a single-age cluster:

Observe the effects of mass on otherwise similar stars

GAIA: Studies of the Solar System

Deep and uniform detection of all moving objects:

- complete to 20 mag
- discovery of ~10^5 - 10^6 new objects (cf. 65,000 presently)
- taxonomy and mineralogical composition versus heliocentric distance
- diameters for ~1000 asteroids
- masses for ~100 objects
- orbits: 30 times better than present, even after 100 years
- Trojan companions of Mars, Earth and Venus
- Edgeworth-Kuiper Belt objects: ~300 to 20 mag + binarity + Plutinos
- Near-Earth Objects:
  - e.g. Amors, Apollos and Atens (442: 455: 75 known today)
  - ~1600 Earth-crossing asteroids > 1 km predicted (100 currently known)
  - GAIA detection: 260 - 590 m at 1 AU, depending on albedo

GAIA: Discoveries of Extra-Solar Planets

- Large-scale detection and physical characterisation
- 20,000- 30,000 giants to 150-200 pc

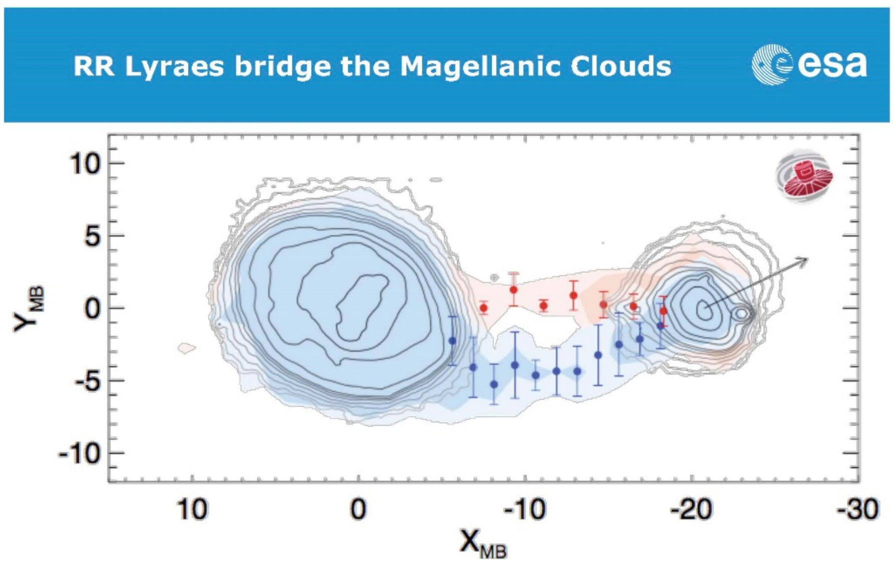
  e.g. 47 UMa: astrometric displacement 360 μas
- complete census of all stellar types (P = 2-9 years)
- masses, rather than lower limits (m sin i)
- orbits for many (≈5000) systems
- relative orbital inclinations for multiple systems
- mass down to 10 M_{Earth} to 10 pc

Galaxies, Quasars, and the Reference Frame

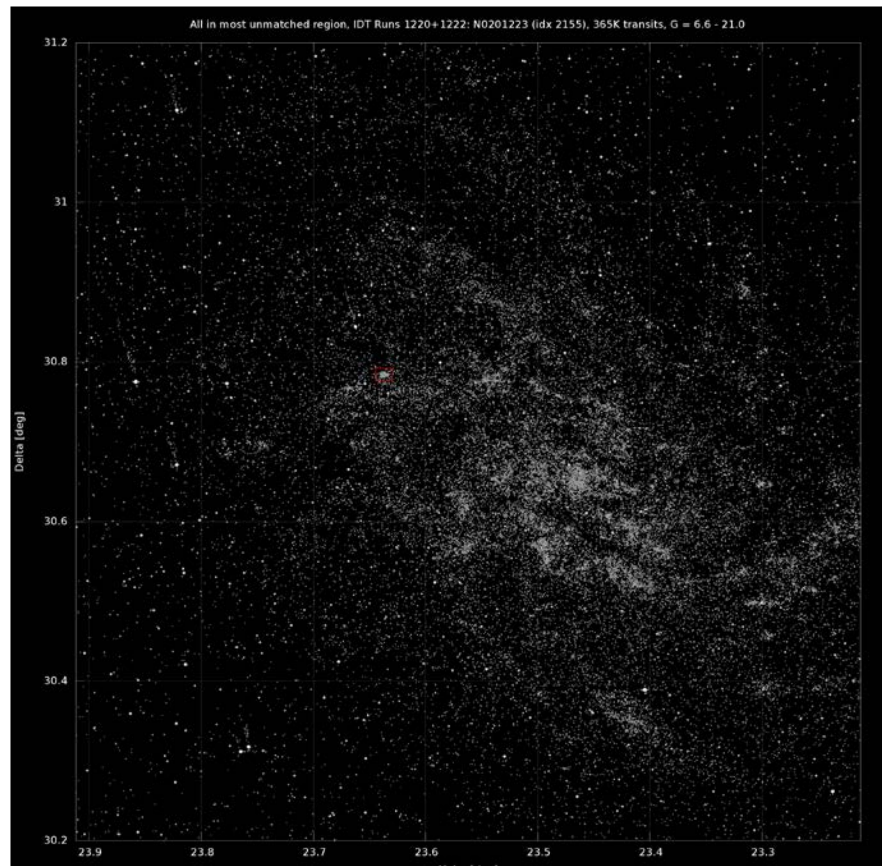
- Parallax distances, orbits, and internal dynamics of nearby galaxies
- Galaxy survey, including large-scale structure
- ~500,000 quasars: kinematic and photometric detection
- ~100,000 supernovae
- Ω_M, Ω_Λ from multiple quasar images (3500 to 21 mag)
- Galactocentric acceleration: 0.2 nm/s^2 $\Rightarrow$ Δ(aberration) = 4 μas/yr
- Globally accurate reference frame to ~0.4 μas/yr

Dark energy?

1.8.5 Orbits in the Local Group: Gravitational Instability in the Early Universe The orbits of galaxies are a result of mildly non-linear gravitational interactions, which link the present positions and velocities to the cosmological initial conditions. It is uniquely possible in the Local Group to determine reliable three-dimensional orbits for a significant sample of galaxies, in a region large and massive enough to provide a fair probe of the mass density in the Universe. Such orbital information provides direct constraints on the initial spectrum of perturbations in the early Universe, on the global cosmological density parameter Ω, and on the relative distributions of mass and light on length scales up to 1 Mpc.



Find RR Lyrae variables from G magnitude errors!
Belokurov et al., 2016, MNRAS (arXiv:1611.04614v1) gaia European Space Agency



General Relativity/Metric

- From positional displacements:
  - γ to 5×10^{-7} (cf. 10^{-5} presently) $\Rightarrow$ scalar-tensor theories
  - effect of Sun: 4 mas at 90°; Jovian limb: 17 mas; Earth: ~40 μas
- From perihelion precession of minor planets:
  - β to 3×10^{-4} - 3×10^{-5} ($\times$10-100 better than lunar laser ranging)
  - Solar J_2 to 10^{-7} - 10^{-8} (cf. lunar libration and planetary motion)
- From white dwarf cooling curves:
  - dG/dT to 10^{-12} - 10^{-13} per year (cf. PSR 1913+16 and solar structure)
- Gravitational wave energy: $10^{-12} < f < 10^{-9}$ Hz
- Microlensing: photometric (~1000) and astrometric (few) events
- Cosmological shear and rotation (cf. VLBI)

GAIA Observatory: Early Science

- **Continuously throughout the mission:**
  - broad-band photometry
  - medium-band photometry
  - radial velocity spectroscopy

=> VARIABLES, INTERESTING OBJECTS, SOLAR SYSTEM SOURCES, SUPERNOVAE,…

⇒ A REAL-TIME VIDEO OF THE SKY at 0.1arcsec resolution...

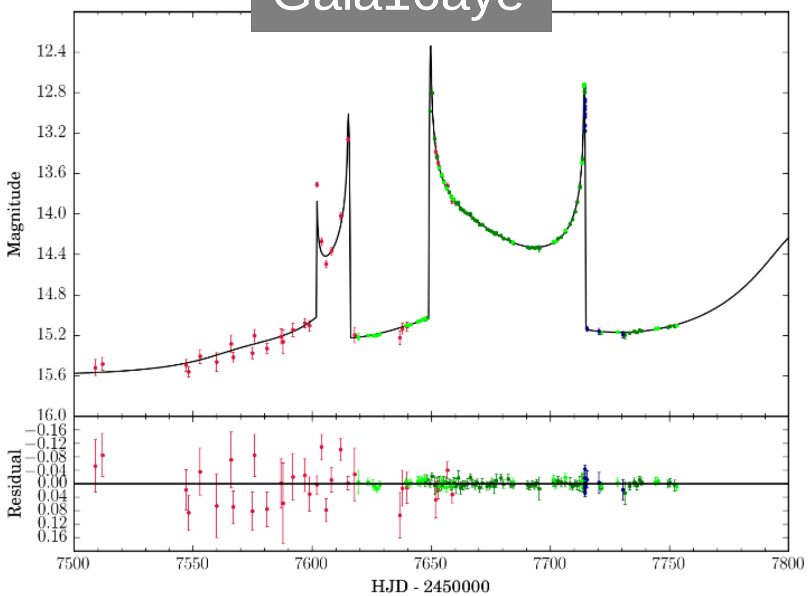
Gaia daily science alerts
https://gaia.ac.uk

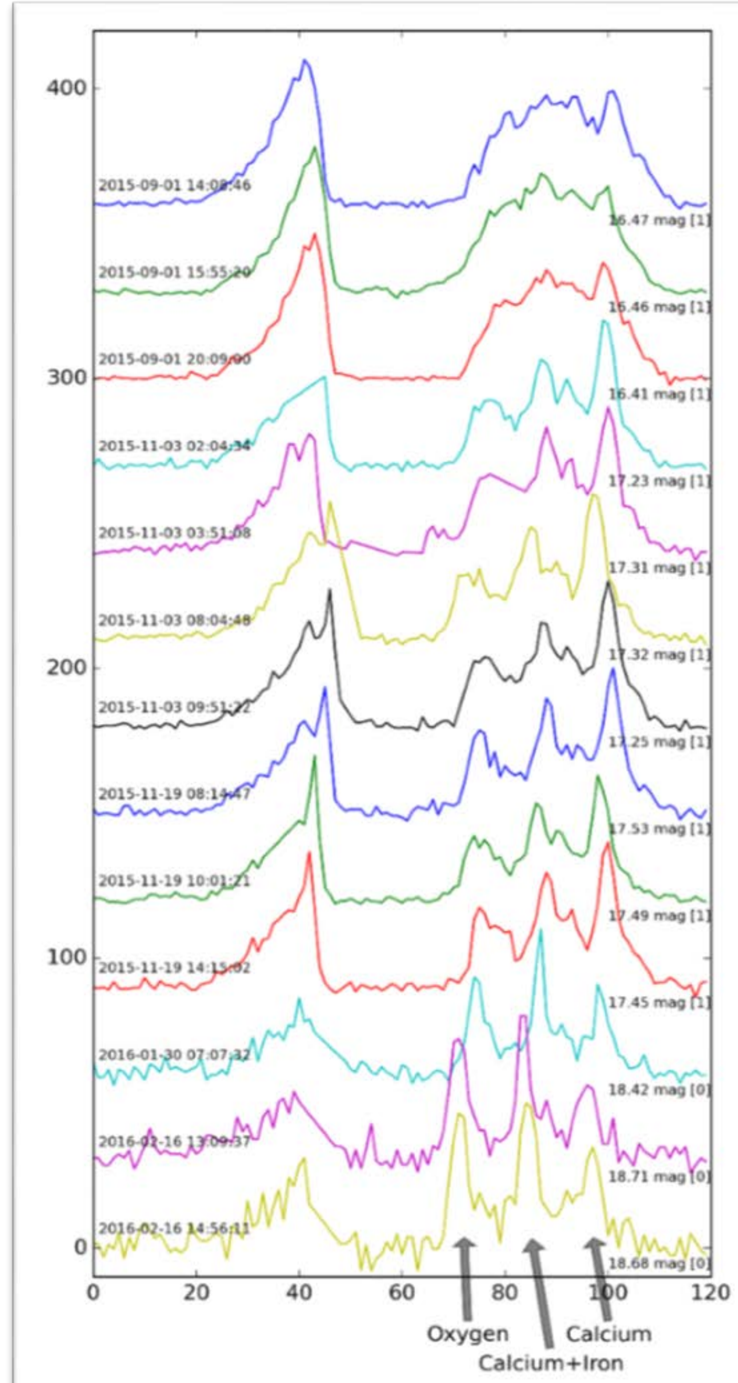
Gaia spectrophotometry
350 – 1020nm

Gaia 16aeg - Transition from supernova to nebular spectrum

Data are NOT flux corrected

Gaia16aye





Get the GaiaAlerts smartphone App!

Summary (2000)

GAIA will determine:

- when the stars in the Milky Way formed
- when and how the Milky Way was assembled
- how dark matter in the Milky Way is distributed

GAIA will also make substantial contributions to:

- stellar astrophysics
- Solar System studies
- extra-solar planetary science
- cosmology
- fundamental physics

Summary (2017)

Gaia team has done an excellent job explaining how to use Gaia data

“Bayesian” dominates the wordcloud

the primary legacy of DR1

After 25 years work by the Gaia project team, science results *free for all* are starting

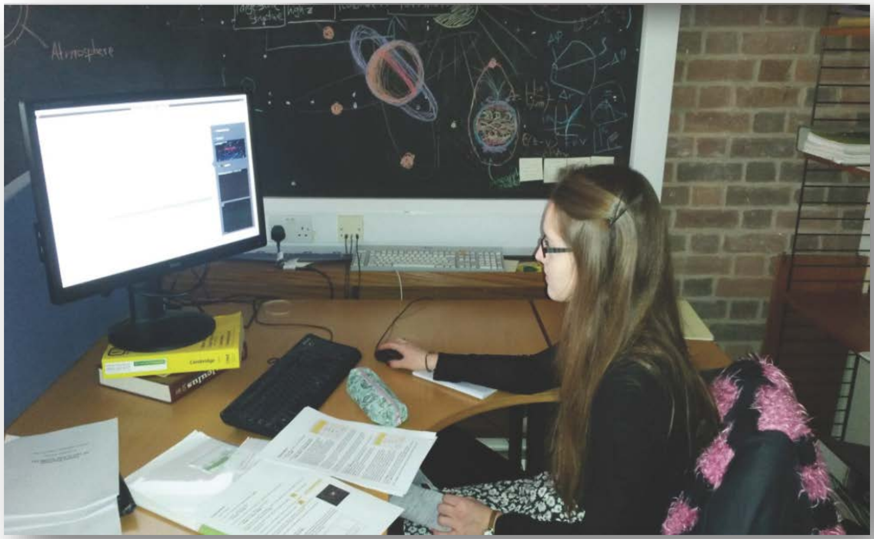
The people behind Gaia

Gaia science: learning how to learn

Science results – new sources, supernovae directly to the public.

For schools, amateurs, anyone….

https://gaia.ac.uk is a simple interface to all Gaia science



We are working with global robotic telescopes available for school educational use to follow-up Gaia discoveries.

School classes can learn science by doing original science. "Adopt a Supernova"

follow Copernicus:
learn from data,
not preconceptions.